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Locating the Temperature Switch for a Drag Reducing Solution

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Abstract

Low-cost and environmentally friendly district heating has become a popular trend in northern Europe. These systems use excess heat from plants or factories to heat water, which is then used to supply heat to homes and buildings in the surrounding area. To decrease costs in these systems, studies have shown that a drag reducing surfactant additive can be added to the hot water in order to increase the flow rate without requiring additional pumping energy. However, due to their tendency to reduce turbulent mixing, drag reducing solutions are not typically effective heat transfer fluids. For this reason, it is desirable to develop drag reducing solutions with switchable properties such that they will be drag reducing in part of the district heating system and non-drag reducing in other sections. In this study two solutions were developed showing less than 1 degree Celsius temperature switchability.

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1 Introduction

1.1 History of Drag Reduction

Turbulent drag reduction is the phenomenon that occurs when an additive causes a decrease in turbulent friction [1]. The solution still has a turbulent flow; however, it experiences properties of a laminar fluid. As a result, there is also a reduction in pressure drop, meaning the need for pumping energy is decreased.

Drag reduction been studied for over eight decades [2]. The first report of drag reduction was in 1931 by Forrest and Grierson [3]. They reported to have seen a significant decrease in energy loss using wood pulp fiber suspensions additives in turbulent water flow; however, their findings went unnoticed [3]. In 1971, Mysels added an aluminum disoap to gasoline flowing in pipes, and the result was the first recognized phenomenon of drag reduction [3]. Toms completed similar studies on the addition of the polymer polymethyl methacrylate to monochlorobenzene and reported his results at the First International Rheological Congress [3]. Toms reported observations of an increase in flow rate with constant pressure with the addition of polymers; the phenomenon of drag reduction was then named Toms Effect [3]. Savins eventually coined the term drag reduction [4]. Following this, the study of drag reducing additives increased exponentially, and many additives were discovered and tested. The additives that will be discussed in this introduction are aluminum soap, polymer, and surfactant drag reducing additives.

1.2 Aluminum Soaps

As mentioned above, Mysels ran experiments on aluminum disoaps on gasoline. Two effective aluminum drag reducing additives include aluminum dioctate and aluminum di-2-methylundecanoate [5]. In 1975, aluminum dioctate was added to toluene, and its effects on drag reduction were analyzed [5]. The results showed that the aluminum soap additive reduced drag up to 80.0% while only requiring an additive concentration of 0.08% [5]. Aluminum di-2-methylundecanoate was also proven to be effectively drag reducing up to 74.0% while maintaining stability over time and shear stress [5].

Despite these breakthroughs, aluminum drag reducing additives are not commonly used due to the discovery of the more efficient polymers [6].

1.3 Polymers

Polymers reduce drag because of their ability to be stretched and uncoiled from their resting position in response to the stress exerted on them by the flowing liquid [7]. The fluid with the added polymer's elongational viscosity, or its resistance to an elongational flow, is significantly increased compared to the elongational viscosity of the fluid alone [7]. This, in turn, causes a reduction in drag [7].

Drag reduction with the addition of polymers was first discovered by Toms, who found the addition of polymethyl methacrylate in monochlorobenzene reduced drag by up to 80% [3]. Polymer drag reduction became increasingly popular in the 1960s through the 1980s and peaked in 1977 due to the oil

crisis in 1973-1974 [3]. In the 1980s, applications such as district heating and cooling were particularly of interest for polymer drag reducing additives [3].

Two types of drag reducing polymer additives exist: Type A and Type B [8]. In Type A, drag reduction occurs in the fully developed turbulent region, and in Type B, drag reduction occurs in the extended laminar region [3].

In general, as the concentration of polymers increases, so too does the drag reduction effect, until the solution reaches its saturation concentration [3]. Beyond this point, an increase in polymer concentration will lead to a drop off in drag reduction [9]. In addition, in order for polymers to be effective drag reducing additives, they must have a molecular weight of at least 10^5 g/mol [10]. As the molecular weight of the polymer additive is increased, as is its drag reducing effects [3].

Polymer drag reducing additives also have a downside; once exposed to stress and the polymers degrade, they are unable to put themselves back together [3]. In particular, longer chained polymers, though more effective at reducing drag, are not very effective in holding a micelle shape when subjected to stress [11]. In fact, with increasing molecular weight, the sensitivity to stress and following degradation increases [11]. This makes polymer additives not very useful in a recirculating system where they would be exposed to the shear stress of a pump. Because of this, surfactants became a point of interest.

1.4 Surfactants

1.4.1 Structure

Surfactants are considered amphiphilic because of their structure that includes a hydrophobic, or nonpolar, tail and a hydrophilic, or polar, head [3]. Because of this structure, when many of these surfactants exist in a solution, the hydrophobic tails tend to gather together while the hydrophilic heads move to the boundary, creating a circular assembly called a micelle [3]. When the critical micelle concentration (CMC_I) is reached, spherical micelles are formed. When the concentration increases beyond the CMC_{II} , the micelles lose their spherical shape and form wormlike shapes [3]. When they reach this point, the micelles are considered drag reducing.

Temperature also plays a role in this transition. At a temperature above the Kraft point and a concentration above the CMC_I , spherical micelles can form; as the concentration increases above the CMC_{II} , wormlike micelles can form [6]. As the temperature is increased, the concentration must also be increased in order to reach the wormlike shape to be drag reducing [6]. An illustration of this transition can be seen in Figure 1.

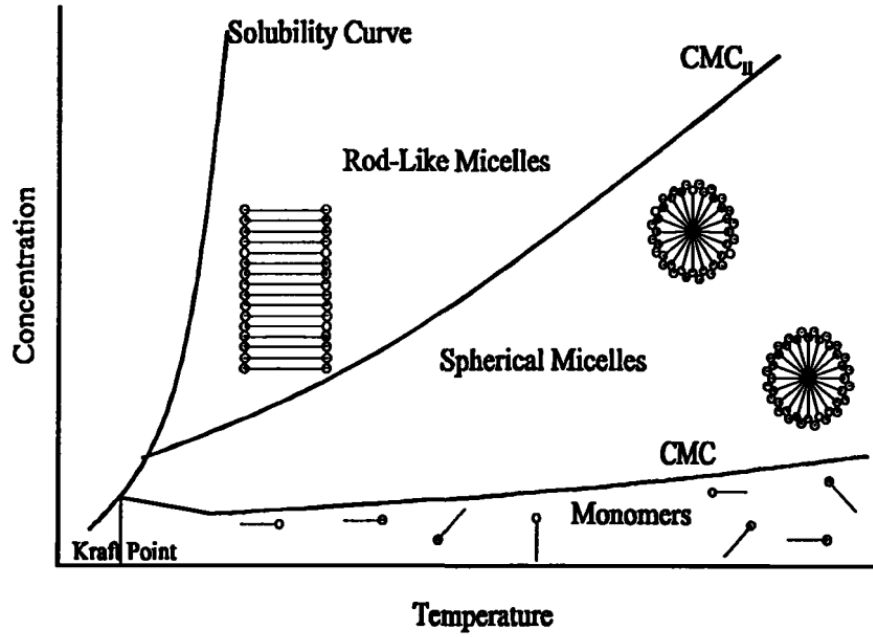


Figure 1: Visual of CMC [6]

A general trend followed by the micelles is that as temperature decreases and concentration increases, the length of the wormlike micelles increases [12].

1.4.2 Types of Surfactants

There exist two different kinds of surfactants: nonionic and ionic [3]. Ionic surfactants include anionic, cationic, and zwitterionic surfactants [3].

- Nonionic surfactants have no charge and therefore do not interact as much with other ions; as a result, only a small range of temperatures has been proven drag reducing [6]. In 1994, Hellsten and Harwigsson experimented with RMA-m and OMA-m, ethoxylated fatty acid ethanolamide

surfactants, and concluded that the former was most drag reducing at higher temperatures, and the latter was most drag reducing at lower temperatures [13]. They concluded that these ethoxylated fatty acid ethanolamides would work well in district cooling systems due to their biodegradability and lack of effect on marine life [13].

- Anionic surfactants are most effective in hydrocarbon solutions [3]. In order to be drag reducing, large concentrations of the anionic surfactant are needed, which increases costs [3]. In addition, anionic surfactants precipitate in the presence of calcium and magnesium, which are found in tap water, meaning they will not work well with aqueous solutions [6]. Furthermore, when exposed to air, anionic surfactants have a tendency to foam, leading to issues in applications [6].
- Cationic surfactants are effectively drag reducing when mixed with counterions [3]. Unlike nonionic surfactants, cationic surfactants are drag reducing over a large range of temperatures, and unlike anionic surfactants, cationic surfactants do not precipitate in the presence of calcium and magnesium [6]. The most common counterions studied include sodium salicylate [3] and a solution of Ethoquad O-12 mixed with sodium salicylate [14].
- Zwitterionic surfactants are unique in that they are both positively and negatively charged [3]. Studies performed have shown that zwitterionic surfactant systems can be drag reducing between 8 and 50 degrees Celsius and are biodegradable and have little effect on marine life [15].

In conclusion, the only plausible surfactants for applications (which will be discussed in the following section) are cationic and zwitterionic surfactants.

1.5 Applications

1.5.1 District Heating and Cooling

District heating and cooling systems provide heating or cooling to homes by running heated or cooled water through pipelines underneath buildings and homes [3]. Of the total energy used for district heating and cooling, the pumping and recirculating of the water takes up 15%, so for this reason, it would be optimal to decrease friction to reduce the amount of energy needed to pump the fluid [3]. It has been found that surfactant drag reducing additives have the biggest effect on reducing drag [3] and are most effective with systems that have minimal branching [1]. They have been found to reduce energy for recirculation by 50-70% [3].

Large scale implementation has been completed in the past [3]. In Herning, Denmark, a district heating system was injected with surfactant drag reducing additives [16]. The result was a 70% reduction in pumping energy [16]. In Volklingen, Germany [17] and Prague, Czech Republic [18], similar studies were performed.

In Japan, it was reported in 2010 that cationic surfactants are used in more than 130 buildings to decrease energy needed to pump by 20-60% [19].

1.5.2 Oil Pipes

Burger began experimentation in 1979 on polymer additives effects on drag reduction in oil pipes [20]. The polymer used was a CDR drag reducer, which is a high molecular weight polymer in a hydrocarbon solvent [20]. The polymer additive was a success. The polymer was injected in an 800 mile long Alyeska pipeline with a diameter of 48 inches which ran from the North slope to South Alaska [3]. The injections were made in multiple locations with concentrations of 5 to 25 ppm, and the result was a 25% increase in capacity of the pipeline of 500,000 barrels of crude oil a day [20].

Polymer drag reducing additives experienced more success in oil pipelines [3]. These pipelines include the Iraq-Turkey, Bass Strait, and Mumbai Offshore pipelines [21]. In addition, the North Sea Offshore pipeline also used these polymer drag reducing additives to increase flow rates [22].

1.6 Significance of Research

The current system being studied is very unique and can be very useful in the above-mentioned applications. The previously mentioned drag reducing additives are all similar in that in order for drag reducing properties to be turned on and off, an external stimulus must be added to the system. With this system and solution, a simple change in temperature can change the drag reducing characteristics. While the system is warm and running through piping, it is drag reducing and experiences high heat transfer reduction (HTR). When the fluid reaches its destination (i.e. a home connected to a district

heating system), the drag reducing properties decrease, along with the HTR, allowing for the heat from the system to be transferred to its destination. The micelles are now degraded. When the fluid makes its way back and is heated again, the micelles reform and become drag reducing once again. This is useful because the micelles are able to degrade and put themselves back together without any addition of additives or external stimuli. For this reason, it is sustainable and cheaper in the long term.

2 Methodology

2.1 Solutions

Two drag reducing solutions were used in this experiment and are described below:

2.1.1 Zwitterionic/Cationic Surfactant

The first solution is a zwitterionic/cationic surfactant (ZwitCat) mixture. The zwitterionic surfactant used was dimethylhexadecylammoniumpropane-sulfonate, also known as SB3-16. This specific surfactant was selected because of its long tail length that matches that of the chosen cationic surfactant. The structure of SB3-16 is shown in Figure 2.

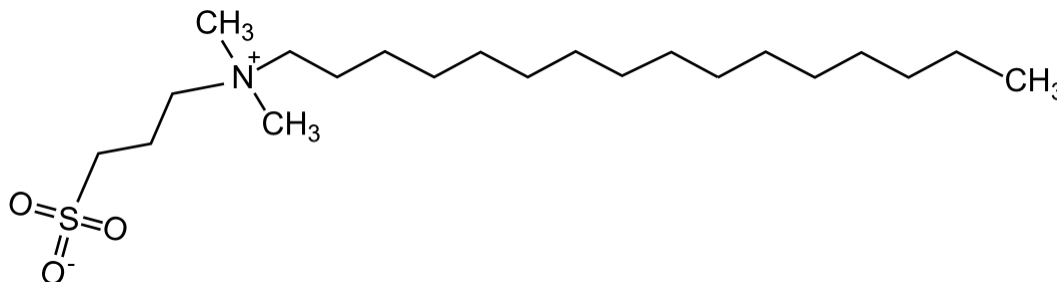


Figure 2: Structure of SB3-16 [23]

The cationic surfactant used was Arquad S-50. This surfactant was chosen because of its well-studied drag reducing properties. The structure of Arquad S-50 is shown in Figure 3.

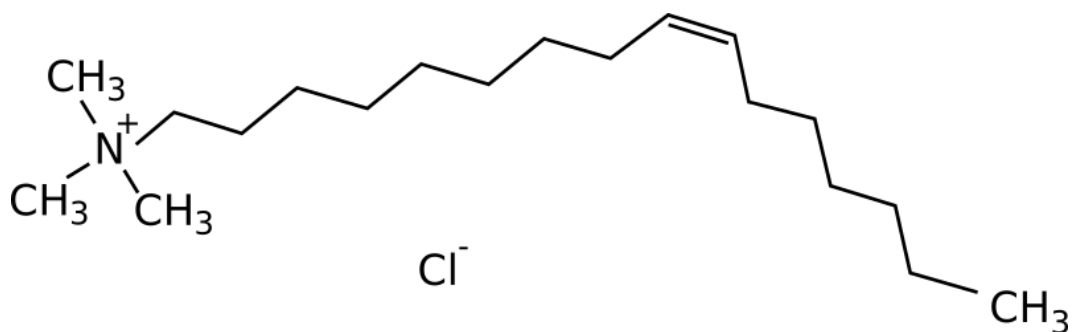


Figure 3: Structure of S-50 [23]

The counterion used in this solution was sodium salicylate, which came in the form of a dry powder. This counterion was chosen because of its ability to bind to micelles. It has been extensively studied in the field of drag reduction. The structure of sodium salicylate is shown in Figure 4.

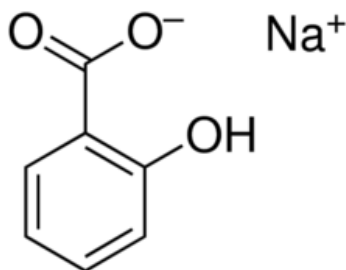


Figure 4: Structure of sodium salicylate [23]

To create this solution, the following procedure was followed:

1. Pour 2L distilled water from CBEC in a 4L Nalgene beaker.
2. Calculate the amount of surfactant to be added.

The molecular weight of SB3-16 is 391.65 g/mol. The molecular weight of Arquad S50 was taken as an average from the Akzo-Nobel literature

as 403 g/mol.

$$(volume) * (concentration) * (ratio) * (surfactant\ MW)$$

$$(10L) * (\frac{0.00425mol}{1L}) * (0.425) * (\frac{391.65g\ SB3-16}{1mol}) = 7.07g\ SB3-16$$

$$(10L) * (\frac{0.00425mol}{1L}) * (0.575) * (\frac{403g\ ArquadS-50}{1mol}) = 9.85g\ Arquad\ S50$$

3. Factor in the surfactant stock fraction. Because the SB3-16 is a powder, it is assumed that the surfactant stock fraction is equivalent to 1. According to Akzo-Nobel literature, the surfactant stock fraction for Arquad S-50 is 50%, however, over time, the concentration has dropped to 20%.

$$\frac{9.85g\ Arquad\ S-50}{0.2\frac{g\ Arquad\ S-50}{g\ stock}} = 49.25g\ Arquad\ S-50$$

4. Tare a weighing dish, add the appropriate amount of SB3-16, and weigh the dish again to confirm 7.07g SB3-16. Add the surfactant to the beaker.
5. Tare a 10mL glass syringe, fill it with the appropriate amount of Arquad S-50, wipe with a Kimwipe, and weigh the syringe again to confirm 49.25g Arquad S-50. Add the surfactant to the beaker.
6. Calculate the amount of counterion to be added.

$$(volume)*(surfactant\ concentration)*(ratio)*(sodium\ salicylate\ MW)$$

$$(10L) * (0.00425 \frac{mol}{L}) * (\frac{1.67mol\ counterion}{1mol\ surfactant}) * (\frac{160.11g\ sodium\ salicylate}{1mol})$$

= 11.4g sodium salicylate

7. Tare a weighing dish, add the appropriate amount of sodium salicylate, and weigh the dish again to confirm 11.4g sodium salicylate. Add the counterion to the beaker.
8. Move the contents of the beaker into a 5 gallon bucket and add 8L distilled water. Place the bucket under a high shear disperser and lower the high shear disperser as far as possible to avoid air from getting into the solution.
9. For 60 seconds, allow the high shear disperser to agitate the solution at maximum speed.
10. Place the immersion circulator into the bucket and set it to 40 degrees Celsius for 2 hours or until uniformly mixed.
11. Allow the solution to sit for 24 hours.

2.1.2 Cationic Surfactant

The second solution created is a cationic mixture. The cationic surfactant used was Arquad 16-50 because of its success in previous studies [24]. The stock solution used has a weight percent of 50% Arquad 16-50 and 50% water and isopropanol. The structure of Arquad 16-50 is shown in Figure 5.

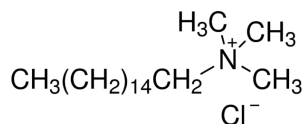


Figure 5: Structure of Arquad 16-50 [25]

The counterion used was 3-chlorobenzoic acid. The Zakin group performed extensive studies comparing 3-chlorobenzoic acid and 4-chlorobenzoic acid [24], and because of the extensive data collected on the counterion, it was chosen for this experiment. 3-chlorobenzoic acid is a crystalline powder. The structure of 3-chlorobenzoic acid is shown in Figure 6.

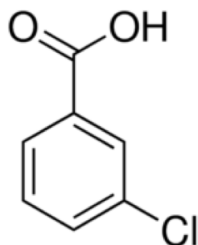


Figure 6: Structure of 3-chlorobenzoic acid [26]

To create this solution, a similar procedure to that of the ZwitCat was used. In this procedure, however, there is no added zwitterionic surfactant, and the respective above mentioned cationic surfactant and counterion are used. In addition, sodium hydroxide was added in order to help the counterion fully dissociate. The concentration of the final solution was 5 mM Arquad 16-50, 5 mM 3-chlorobenzoic acid, and 5 mM sodium hydroxide.

2.2 Flow System

The flow system used in the zwitterionic/cationic surfactant experimentation is shown in Figure 7. The flow system used in the cationic surfactant experimentation is a modified version of Figure 7. For the cationic surfactant experiments, the concentric tube heat exchanger was moved further back on the system in order to give the solution more time to run before it reached the fluted tube heat exchanger, where it was cooled down.

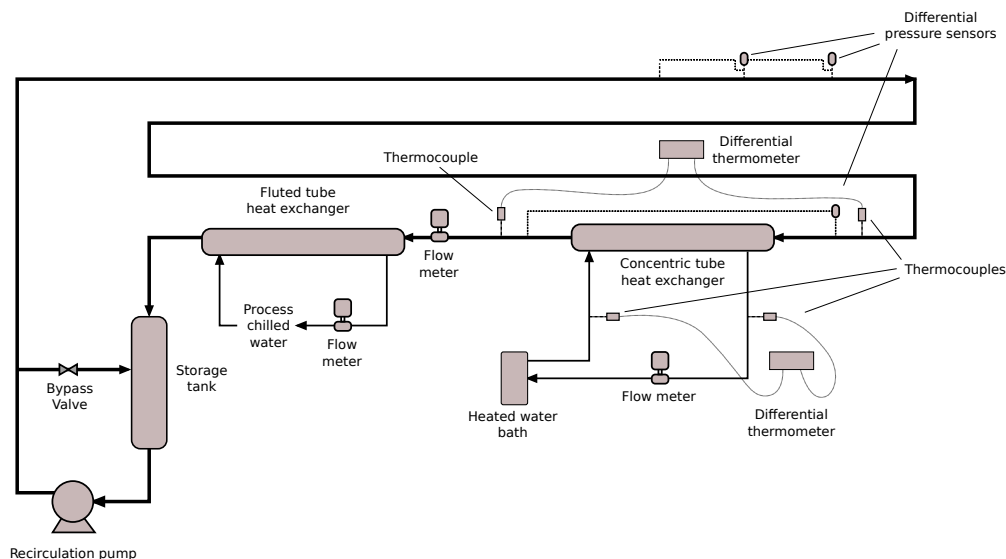


Figure 7: Visual of the flow system [23]

The system is approximately 22 meters in length and contains a 10-liter storage tank to store the solution and a 2-horsepower gear pump to pump the solution. Stainless steel tubing with an inner diameter of 10.2 millimeters and an outer diameter of 12.7 millimeters was used to run the solution through the

system. Two Omega 10 psi PX2300-10DI differential pressure transducers and one 100 psi PX2300-DI differential pressure transducer were used to measure pressure drop. A DaqBoard 2000 data acquisition board was used to export data, which was collected into a spreadsheet to be analyzed.

The fluid runs from the tank through the pump where it passes the pressure sensors. It then runs by Type T thermocouples, which record the fluid’s temperature and display it through the Physitemp BAT-10 Multipurpose Thermometer. The fluid is then run through a concentric tube heat exchanger, where the shell side is supplied with water from a 800 W NESLAB RTE-111 heated water bath. A VWR 1120 immersion circulator was added to the water bath to increase the amount of heat provided.

The fluid then runs through a Toshiba LF404 electromagnetic flowmeter which reads its volumetric flow rate with +/- 0.5% accuracy, according to the instruction manual. Following the flowmeter, the fluid’s temperature is read again, and it runs through the fluted tube heat exchanger where it is cooled down by process chilled water. The fluid then flows once again into the tank.

2.3 Drag Reduction Measurements

Drag reduction ($DR\%$) is the difference in the friction factor of a pure solvent and the drag reducing solvent divided by the friction factor of the drag reducing solution. $DR\%$ is expressed as:

$$DR\% = \frac{f_{water} - f}{f_{water}} * 100\%$$

where f_{water} is the water friction factor and f is the drag reducing solution friction factor. f_{water} was calculated using the Prandtl-Karman equation:

$$\frac{1}{\sqrt{f}} = 4 \log_{10}(Re \sqrt{f}) - 0.4$$

where f is the Fanning friction factor and Re is Reynolds number, which is calculated:

$$Re = \frac{\rho v D}{\mu}$$

where ρ is density, v is mean linear velocity, D is hydraulic diameter, and μ is dynamic viscosity. The friction factor of the drag reducing solution was calculated using the Fanning friction factor definition:

$$f = \frac{2\tau}{\rho v^2}$$

where τ is wall shear stress, ρ solvent density, and v is mean linear velocity. The wall shear stress, τ , is determined by:

$$\tau = \frac{\Delta P D}{4L}$$

where ΔP is pressure drop, D is diameter of conduit, and L is the length of the pressure drop. D and L are known because they are constant measurements of the system. ΔP is unknown and must be measured by the pressure sensors.

2.4 Heat Transfer Reduction Measurements

Heat transfer reduction ($HTR\%$) is the difference between the Nusselt number of a pure solvent and the Nusselt number of the drag reducing solution, divided by the Nusselt number of the pure solvent. $HTR\%$ is expressed as:

$$HTR\% = \frac{Nu_{water} - Nu}{Nu_{water}} * 100\%$$

where Nu_{water} is the Nusselt number of water and Nu is the Nusselt number of the drag reducing solution. The Nusselt number can be calculated:

$$Nu = \frac{hD}{k}$$

where h is the convective heat transfer coefficient, D is the hydraulic diameter, and k is the thermal conductivity of the solution. Because the thermophysical properties of water were used, the calculation of $HTR\%$ can be written:

$$HTR\% = \frac{h_{water} - h}{h_{water}} * 100\%$$

To determine the value of h , the work in the concentric tube heat exchanger was used.

3 Results

3.1 Temperature Switch

3.1.1 Zwitterionic/Cationic Surfactant

Using the ZwitCat solution created above, a Reynolds number sweep was performed at several temperatures in order to determine whether or not temperature had an effect on drag reduction. Drag reduction and heat transfer reduction measurements were taken. The results are shown in Figure 8.

At a temperature of 40 degrees Celsius, the solution experiences drag reduction. As the Reynolds number is increased, the solution slowly becomes more drag reducing. A small curve is formed as Reynolds number is increased, and it plateaus around 30,000 to 40,000 Re at about 65-70% drag reduction. The heat transfer reduction follows the drag reduction curve.

The solution run at 26.5 degrees Celsius is not consistently drag reducing at every Reynolds number. From 10,000 to about 22,500 Re, the solution is about 0% drag reducing. At approximately 25,000 Re, the solution experiences a sharp increase in drag reduction to about 50%. The heat transfer reduction does not experience this jump and remains at 0% over the course of the Reynolds number sweep.

The solution run at 25 degrees Celsius does not experience any drag reduction or heat transfer reduction throughout the entire course of the Reynolds number sweep.

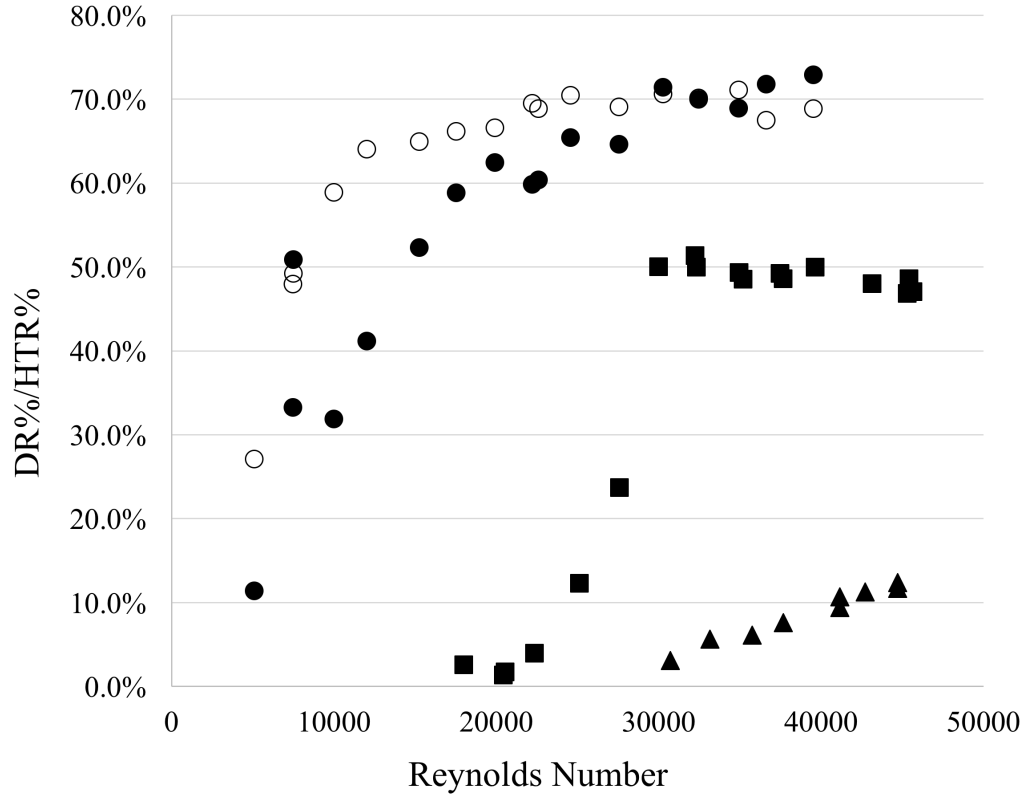


Figure 8: Zwitterionic/Cationic Surfactant Trial 1: filled shapes represent DR; unfilled shapes represent HTR; circles represent the solution at 40 degrees Celsius; squares represent the solution at 26.5 degrees Celsius; triangles represent the solution at 25 degrees Celsius.

To investigate the effect of temperature further, a temperature sweep was performed where the volumetric flow rate was held constant at about 4 gallons per minute while the temperature of the solution was decreased from 30 degrees Celsius to 25 degrees Celsius and then increased from 25 degrees Celsius to 30 degrees Celsius. The results of this experiment are shown in Figure 9.

At this flow rate, the drag reduction decreased and increased from about 15% to a maximum of 74%. The off switch in drag reduction occurred in less

than one degree between 25 and 26 degrees Celsius. The on switch in drag reduction also occurred in less than one degree between 26 and 27 degrees Celsius.

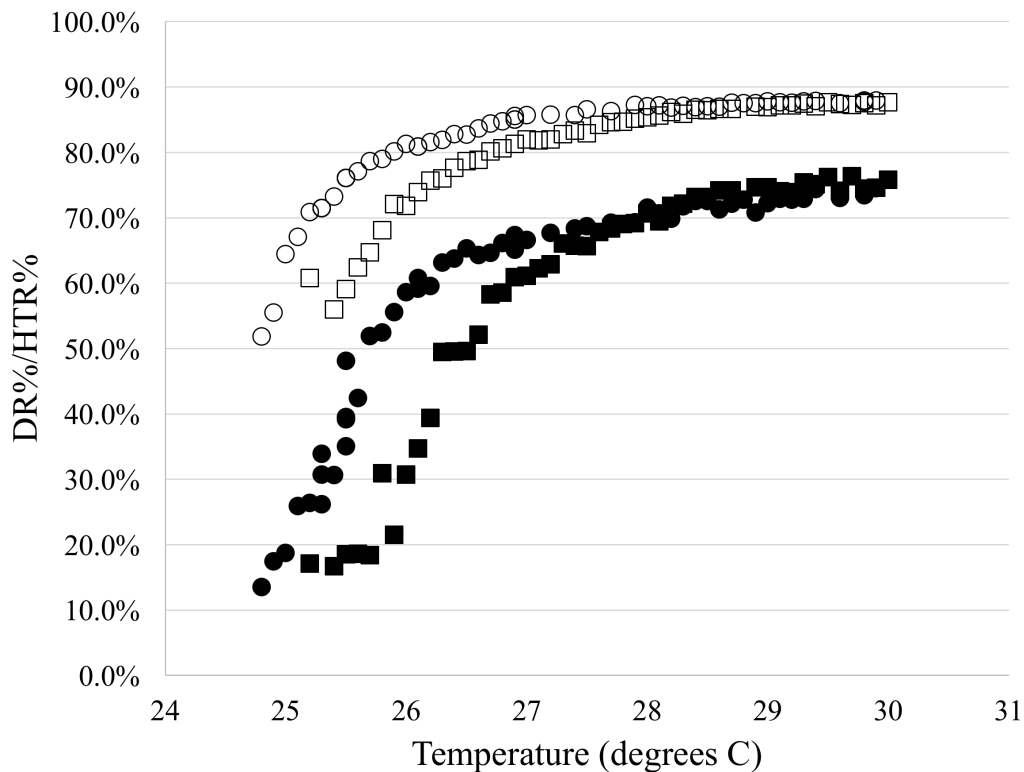


Figure 9: Zwitterionic/Cationic Surfactant Trial 2: filled shapes represent DR at 4gpm; unfilled shapes represent HTR at 4gpm; circles represent decreasing temperature; squares represent increasing temperature.

3.1.2 Cationic Surfactant

Similar testing was performed on the 3-chlorobenzoic acid and Arquad S50 solution. First a sweep of Reynolds numbers was taken at two different

temperatures. The results of the experiment are shown in Figure 10. At 21.3 degrees Celsius, the drag reduction and heat transfer reduction remained at 0% for the entirety of the sweep. At 27.6 degrees Celsius, the drag reduction increases with increasing Reynolds Number. Also at this temperature, the heat transfer rate remains at 0%.

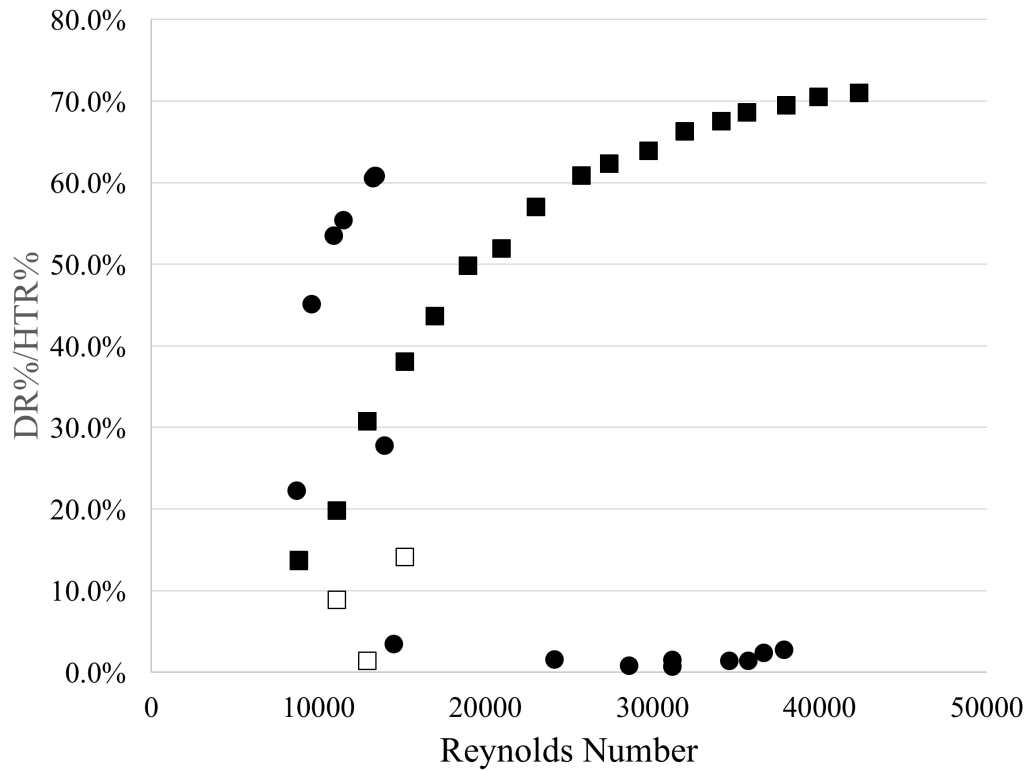


Figure 10: Cationic Surfactant Trial 1: filled shapes represent DR; unfilled shapes represent HTR; circles represent the solution at 21.3 degrees Celsius; squares represent the solution at 27.6 degrees Celsius.

Again, the temperature switch was further investigated. A temperature sweep was performed at 30,000 Re. The results of the experimentation are displayed in Figure 11. As the solutions temperature was increased, it experi-

enced a sharp increase from 5% to 71% drag reduction at 24.6 degrees Celsius. At two tenths of a degree lower, the solution was non-drag reducing at 5%. In addition, the solution increased from 19% to 85% in heat transfer reduction. Similarly, two tenths of a degree lower, heat transfer reduction was measured at 8%.

The solution's temperature was then decreased. As a result, the solution experienced a sudden drop from 86% to 22 % heat transfer reduction. Following this, the solution went from drag reducing to non-drag reducing almost instantly at 23.3 degrees Celsius, dropping from 66% to 4% drag reducing.

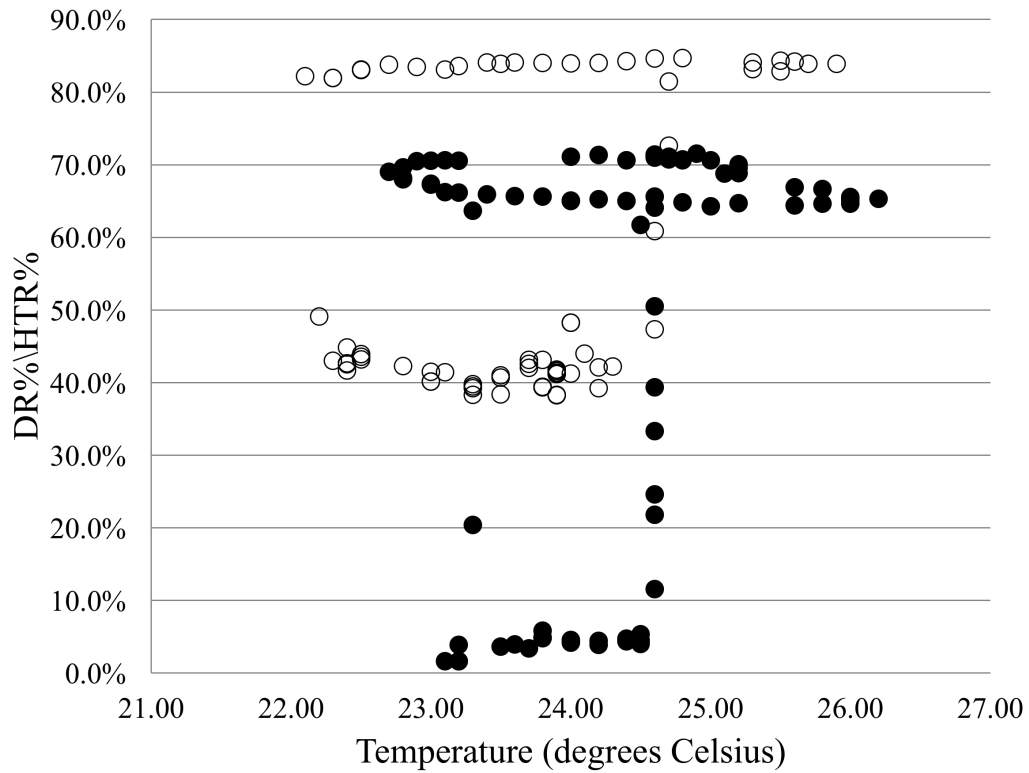


Figure 11: Cationic Surfactant Trial 2: filled circles represent DR at 30,000 Re; unfilled circles represent HTR at 30,000 Re.

3.2 Hysteresis

Hysteresis is evident in both the zwitterionic/cationic and cationic surfactant solutions.

As mentioned, in Zwitterionic/Cationic Surfactant Trial 2, the temperature began at 30 degrees Celsius, where DR was on, and was decreased until DR turned off and then was increased until DR turned back on. The temperatures at which point the DR turns on and off differ by about one degree. The DR turns off between 25 and 26 degrees Celsius from 13% to a maximum of 75%.

The solution's DR then turns back on between 26 and 27 degrees Celsius from 17% to a maximum of 76%. This can be seen in Figure 9.

Similarly, in Cationic Surfactant Trial 2, the temperature was first increased until drag reduction turned on and then decreased until drag reduction turned off. The temperatures at which these two switches occur differ. Upon increasing the temperature, the drag reducing properties turn on at 24.6 degrees, where the solution goes from 5% to 71% drag reducing. Upon decreasing the temperature, the solution's drag reducing properties turn off at 23.3 degrees Celsius, where the solution goes from 66% to 4 % drag reducing. This can be seen in Figure 11.

4 Discussion

4.1 Temperature Switch

4.1.1 Zwitterionic/Cationic Surfactant

In Zwitterionic/Cationic Surfactant Trial 1 shown in Figure 8, it was showed that the ZwitCat solution's drag reducing properties are in fact sensitive to temperature. A deeper look at this, shown in Zwitterionic/Cationic Surfactant Trial 2 in Figure 9, shows that the solution is actually very sensitive to temperature and can become drag reducing within one degree Celsius between 26 and 27 degrees Celsius.

While the reason for this is unknown, there is speculation as to why this temperature switch occurs in the ZwitCat solution.

It is theorized that the zwitterionic molecule's negative head will fold in on itself to get into closer proximity with the positive group closer to the tail. A study on zwitterionic surfactants showed that bending of the surfactant's head is possible [27]. An illustration of this bending can be seen in Image (b) of Figure 12.

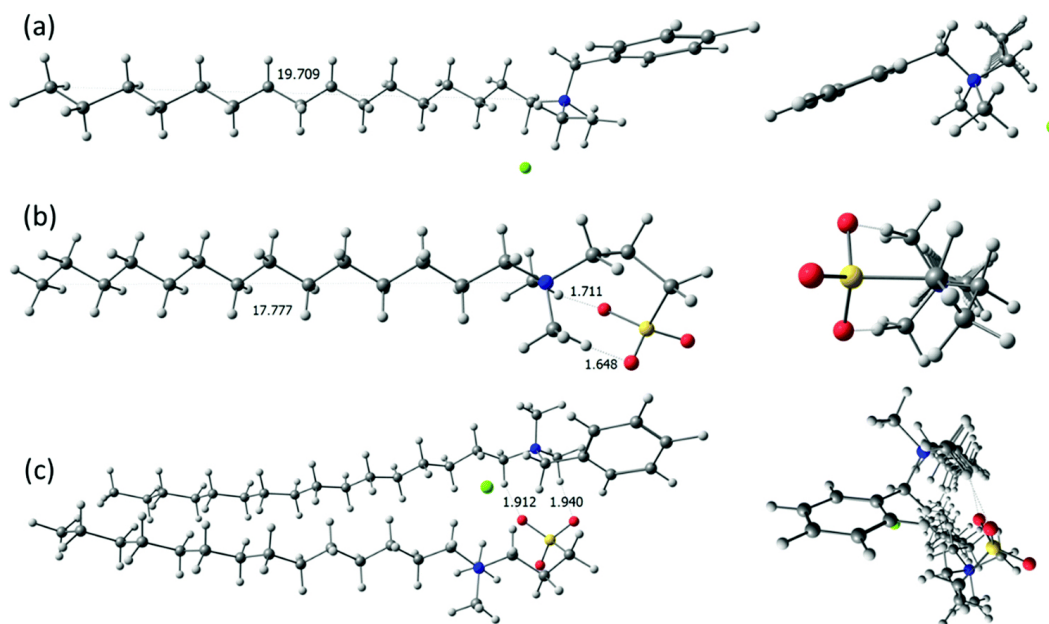


Figure 12: The bending of a zwitterionic surfactant [27]

When it folds, it creates a larger shape that does not fit in with the rod-like micelle structure, and instead forms a spherical micelle shape. For reference, see Figure 1. However, as the temperature is increased, the movement of the surfactants also increases. Because of this increased movement, the head will unfold, allowing the molecule to more easily slide into the rod-like micelle structure, becoming drag reducing.

4.1.2 Cationic Surfactant

In the Zwitterionic/Cationic Surfactant Trial 2, shown in Figure 10, it was shown that the Arquad 16-50 and 3-chlorobenzoic acid solution is also sensitive to temperature. Further investigation led to the conclusion that the

solution experiences a temperature switch at 34.6 degrees Celsius where the drag reduction properties turn on within a half degree Celsius.

The reason for this temperature switch is also unknown, however, theory exists as to why this phenomenon occurs in this solution.

It is speculated that when mixed, the cationic surfactant and counterion combine to form micelles to become drag reducing. When exposed to shear stress, like a pump, the counterion is stripped out of the micelle. The micelle morphology then changes and becomes non-drag reducing. At lower temperatures, the counterion precipitates out and cannot recombine with the cationic surfactant to form micelles. As temperature is increased, the counterion is more able to fall back into solution. At these higher temperatures, because the counterion is dissolved in the solution, it is able to eventually recombine with the surfactant and form micelle structures and become drag reducing once again.

4.2 Hysteresis

Evidence of hysteresis in the switching on and off of drag reduction is apparent. As mentioned above and shown in Figure 11, in the cationic surfactant solution, the drag reducing properties turn on at 24.6 degrees Celsius but turn off at 23.3 degrees Celsius. This difference is greater than one degree Celsius.

The reasoning for this is not proven, however, theories exist. It is hypothesized there is a time-dependence effect on the micelles. It is possible that the reassembly of the micelles is not instant, like the degradation of the micelles.

Another possibility involves the driving force. It is possible an activation

energy-like curve exists, where in order for the micelles to reform into their drag-reducing wormlike structures, they must have enough heat to get to the required activation energy. Until they reach this point, they are in a transition state that is considered non-drag reducing, as they put themselves back together. Upon reassembly, the solution has reached the activation energy needed and are now drag reducing. After this point, the energy (or heat) can drop and the micelles will hold their structure because they have made it over the activation energy hump.

5 Conclusions

5.1 Summary

In summary, through experimentation, it has been proven that drag reducing properties can be turned on with a temperature switch of one degree Celsius or less. In the zwitterionic/cationic surfactant solution of SB3-16, Arquad S-50, and sodium salicylate, it was found that the drag reducing properties could be turned on from 15% to 74% drag reducing from 26 to 27 degrees Celsius at a constant flow rate of 4 gallons per minute. Though the reasoning behind this phenomenon is not known, it is speculated the reason is an increase in temperature causes an increase in molecular movement, causing the foldable head on the zwitterionic surfactant to unfold and form a rodlike micelle structure, therefore becoming drag reducing.

In the cationic surfactant solution of Arquad S50 and 3-chlorobenzoic acid, it was found that the drag reducing properties could be turned on from 5% to 71% drag reducing at 24.6 degrees Celsius at a constant Reynolds number of 30,000. Similarly, the true reasoning is unknown, however, it is theorized that temperature increases counterion solubility, which decreases precipitation of the counterion, meaning the counterion was able to recombine with the surfactant, therefore allowing the solution to become drag reducing.

Hysteresis is apparent in the cationic surfactant solution of Arquad S50 and 3-chlorobenzoic acid; the solution's drag reducing properties turned on at 24.6 degrees Celsius and turned off at 23.3 degrees Celsius, which is over a degree Celsius in difference. The reasoning for this is unknown, however, theories include a time dependence effect and an activation energy theory.

5.2 Future Work

It is recommended that studies be completed on solubility and viscosity on surfactant solutions with counterions that are either poorly soluble in water or exhibit weak binding to micelles. These non-drag reducing surfactants must be understood in order to move forward with drag reduction research.

In addition, it would be beneficial, especially for district heating and cooling systems, if the location of temperature switch could be moved. Not everyone wants their home or building at the same temperature. It would be beneficial if there were a calculated amount of additive that can be added to the system to increase or decrease the temperature point at which drag reduction and heat transfer reduction turns off. In this way, the solution can become drag reducing at temperatures that would actually be circulating in these systems.

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